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Overview of US heavy ion fusion research

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Abstract
Significant experimental and theoretical progress has been made in the US heavy ion fusion programme on high-current sources, injectors, transport, final focusing, chambers and targets for high-energy density physics and inertial fusion energy (IFE) driven by induction linac accelerators. One focus of the present research is the beam physics associated with quadrupole focusing of intense, space-charge-dominated heavy ion beams, including gas and electron cloud effects at high currents, and the study of long-distance-propagation effects such as emittance growth due to field errors in scaled experiments. A second area of emphasis in the present research is the introduction of background plasma to neutralize the space-charge of intense heavy ion beams and assist in focusing the beams to a small spot size. In the near future, research will continue in the above areas, and a new area of emphasis will be to explore the physics of neutralized beam compression and focusing to high intensities required to heat targets to high-energy density conditions as well as for IFE.

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(Some figures in this article are in colour only in the electronic version)

1. Introduction

A coordinated beam physics programme by the Lawrence Berkeley National Laboratory, Lawrence Livermore National Laboratory and Princeton Plasma Physics Laboratory (the Heavy-Ion Fusion Virtual National Laboratory), together with collaborators at Mission Research Corporation, Sandia National Laboratories and the University of Maryland, pursues intense space-charge-dominated beam science in support of applications of heavy ion beams to high-energy density physics (HEDP) and to inertial fusion energy (IFE). A unifying research theme for the US programme is to address a key scientific question of fundamental importance to both HEDP and IFE—'*How can heavy ion beams be compressed to the high intensities required for creating high-energy density matter and fusion ignition conditions*'. The primary scientific challenge is to compress intense ion beams in time and space sufficiently to heat targets to the desired temperatures with pulse durations of order or less than the target hydrodynamic expansion time. Present experiments, theory and simulations investigate key technical issues that can affect the brightness (focusability) of space-charge-dominated beams, including the effects of gas and electron cloud interactions, as well as emittance growth during focusing of such intense beams, including the effects of neutralizing background plasma. Section 2 describes selected highlights of recent research over the last two years. In particular, recent particle-in-cell simulations of planned near-term experiments of modest scale indicate that intense heavy ion beams injected with an appropriate head-to-tail velocity gradient ('tilt') into a long

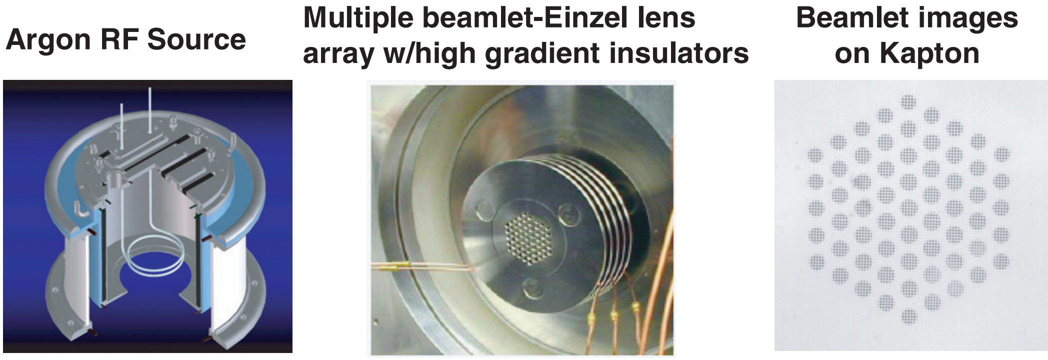

Figure 1. Results on the 100 kV Source Test Stand (STS-100): 61 beamlets extracted from an RF-argon plasma source, through a grid supported by three multi-layer high-gradient insulator stacks (not visible), with brightness and uniformity meeting requirements for heavy ion fusion.

neutralizing background plasma column may be compressed by more than a factor of 100 in length and focused by a factor greater than 20 in radius (>40 000 increase in intensity). Section 3 describes newly developed research plans for the next several years on neutralized beam compression and focusing. Conclusions are given in section 4.

2. Recent research advances

2.1. Source test stand (STS)

Progress has been made both in the generation of high-brightness beamlets for the compact driver-scale injector concept using merging beamlets, as well as in the study of beam optics using large surface ionization sources. High-brightness beamlets of Ar^{+1} ions have been created and measured with current density ($100\,\mathrm{mA\,cm^{-2}}$ @ 5 mA), emittance ($T_{\mathrm{eff}} < 2\,\mathrm{eV}$), charge-state purity (>90% in Ar^{+1}) and energy spread (<0.01%) supporting future merging-beamlet injectors for heavy ion fusion [1]. Sixty-one beamlets were then extracted at 100 kV through four Einzel lens arrays supported by multi-layer, high-gradient insulators with 20% beamlet current uniformity across the array (figure 1). Recently, in December 2004, extraction tests were extended on a 500 kV test stand (STS-500), comparing measured and simulated expansion and merging of 61 beamlets from flat extraction plates (figure 2). The next step will be to extract and accelerate 119 beamlets in converging geometry using curved extraction plates, to test simulations [2] of emittance growth in the transverse merging of beamlet arrays into a converging geometry for compact, high total current injectors. Another experiment was set up on the STS-500 test stand to study the beam optics of an extraction diode using a 10 cm diameter alumino-silicate source [1]. In comparing the experimental results with WARP-3D computer simulations, we found excellent agreement in the emittance diagram (figure 3) and also in the beam current rise time.

2.2. High-current experiment (HCX)

Transport of a very high brightness ($0.4 \leqslant \varepsilon_{\mathrm{n}} < 0.5$ mm-mr), 0.18 A, 1 MeV K^{+} beam shows no emittance growth through five lattice periods of electrostatic quadrupoles (figure 4). Beam loss has been reduced $\sim 3\times$ due to improved injector voltage waveform control and improved envelope control [3, 4]. Envelope simulations for these experiments accurately predict envelope evolution to within measurement uncertainties. In these results (see phase-space measurement inset in figure 4), the beam fills 80% of the physical aperture, an encouraging result for the economic viability of heavy ion fusion. We have also developed and successfully tested prototype superconducting magnets that are well suited for future transport experiments with space-charge-dominated heavy ion beams [5]. Future heavy ion fusion accelerators, as many high-intensity ion accelerators for science today, will need to use magnetic quadrupoles for focusing, raising the possibility of deleterious effects of unwanted electrons attracted into the beam by the strong beam space-charge at high currents. Such electrons can arise from scrape-off of beam ions in the edge of the beam (halo) onto the channel walls, or by ionization of gas desorbed from the wall by any ions lost to the walls. Electron clouds can build up to significant fractions of the beam ion density during $E \times B$ drift times in magnetic quadrupoles, in contrast to electric quadrupoles, where strong transverse electric fields sweep them out quickly. We have begun to study gas and electron cloud effects in HCX with four pulsed magnetic quadrupoles shown in figure 4. We control the level of electron clouds by the positive bias of clearing electrodes placed between each magnet, and we control the ingress of secondary electrons from end diagnostics by an electron suppressor ring at the end, as shown in figure 4.

Experiments involving transport through the four pulsed quadrupole magnets shown in figure 4 began in May 2003, especially to study gas and electron effects [6]. These experiments require matching into a magnetic quadrupole lattice that has a half-period significantly different from that of the upstream electrostatic transport line. Simulations using both envelope and discrete-particle WARP models are guiding the experiments. An efficient electron and ion simulation has been developed to model the detailed dynamics of both electrons and beam ions self-consistently, including a particle advance method with a large time step that can still accurately calculate electron motion in regions where electrons are strongly, weakly and un-magnetized [7]. When the e-suppression voltage is turned off at the end of the four quadrupoles (see figure 4), large electron populations build up in the last magnet, strongly affecting the magnitude and distribution of the beam space-charge, resulting in significant

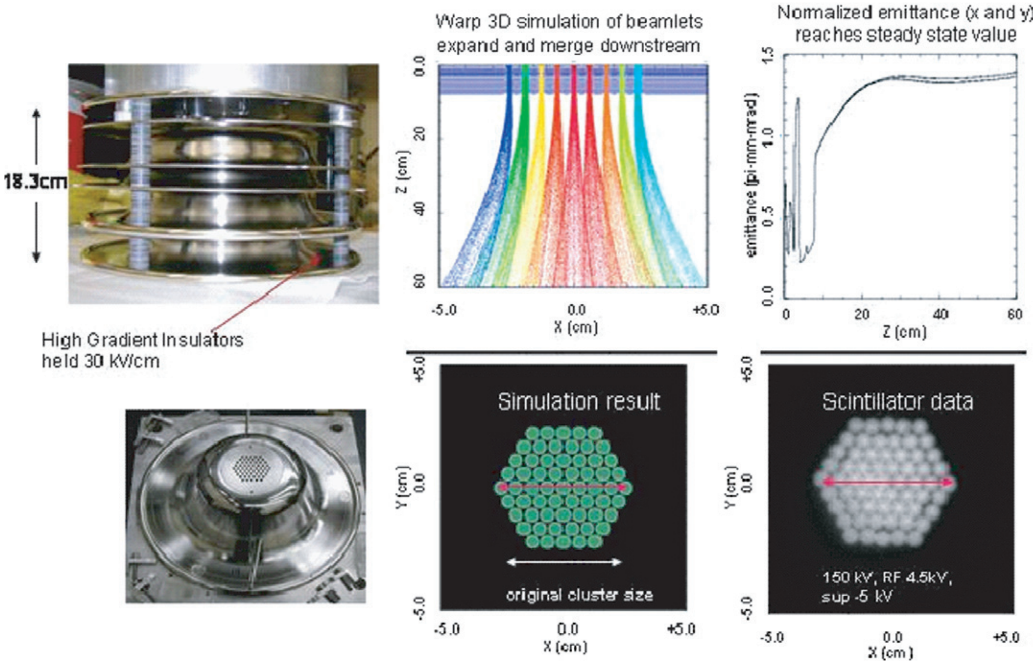

Figure 2. Recent results for extraction and merging of 61 Ar^{+1} beamlets at high-current density > 100 mA cm^{-2} and at full gradient > 100 kV cm^{-1} using flat extraction plates (not yet in converging geometry). Comparisons of simulations and measurements of expansion of the beamlet array due to space-charge are in excellent agreement.

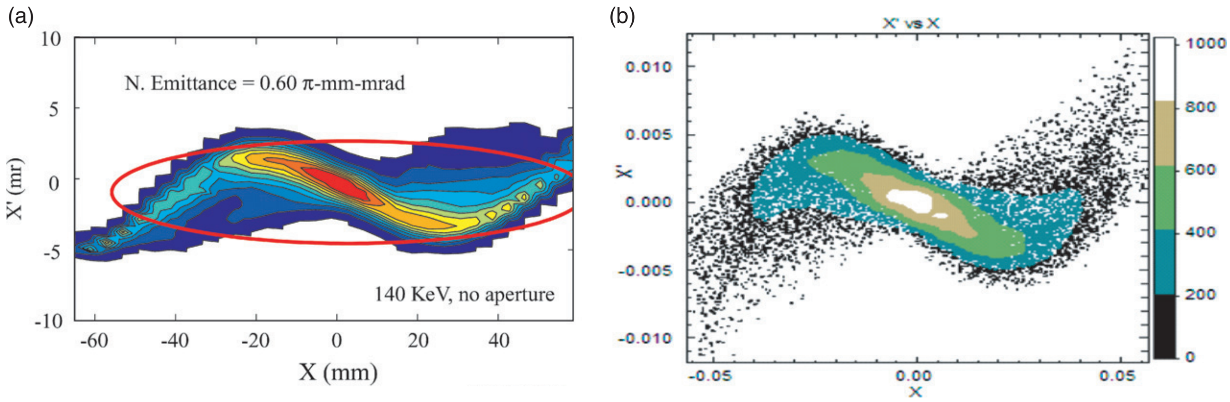

Figure 3. (*a*) Experimental phase-space measured for a single un-apertured beam created with a 10 cm diameter alumino-silicate surface ionization source. (*b*) Warp-three-dimensional particle-in-cell simulation of the experiment depicted in (*a*).

Z-shaped distortions of the beam phase-space exiting the last magnet. Figure 5 compares the beam V_x–x phase-space measured with a slit scanner at the beam exit, with three-dimensional self-consistent simulations [8] of the electron cloud resulting from ingress of secondary electrons coming off the end diagnostics which terminate the beam. The simulations show a distortion of the beam phase-space very similar to that measured. The development of predictive models for electron cloud effects would be useful to any high-current accelerators susceptible to such effects on beam loss.

2.3. Neutralized transport experiment (NTX)

Several recent experiments and studies suggest the feasibility of neutralizing heavy ion beams within the target chamber. A recent experiment [9] shows that stable Z-discharge channels can be created in gas-filled chambers, which might be used both to neutralize and guide a heavy ion beam to the target. Recent studies [10, 11] show that a surrounding insulating wall can aid in ballistic focusing by introducing neutralizing electrons just after a heavy ion beam enters a target chamber. In the NTX at the Lawrence Berkeley National Laboratory, ECR and metal vapour arc plasma sources are used to measure neutralized ballistic focusing to compare with simulations. In NTX, a very high brightness ion beam ($\varepsilon_n < 0.05\pi$ mm-mr at 25 mA, 300 keV K^+), together with neutralization of beam space-charge with preformed plasmas, allows a large reduction of the neutralized beam focal spot to be observed [12], to facilitate benchmarking simulation codes. A MEVVA (‘plug’) plasma source (used just beyond the last focusing magnet) and an RF (‘volume’) plasma source located near the focal plane have been characterized. Figure 6 shows the beam focal spot sizes for three cases of space-charge neutralization: a large focal spot of $\sim$1 cm radius without

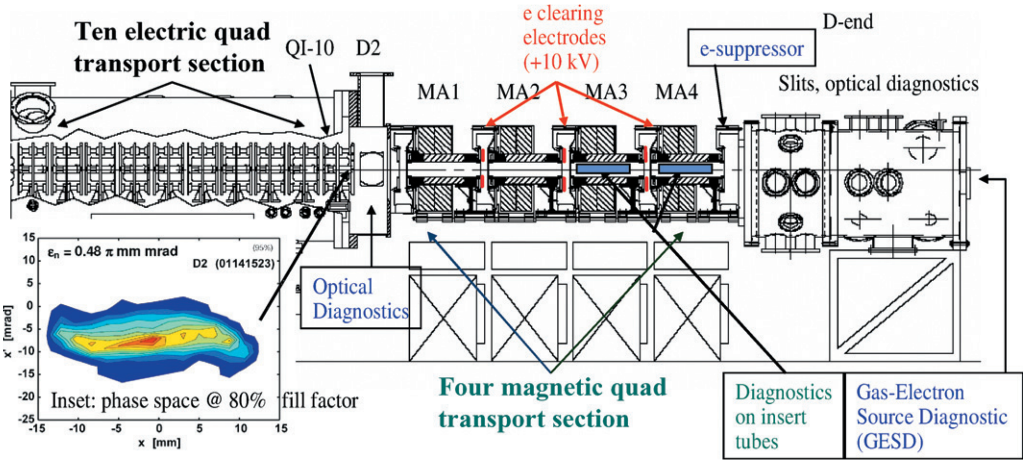

Figure 4. HCX showing the five-lattice period electrostatic transport section and the new four magnetic quadrupole transport section and diagnostic locations where gas and electron cloud experiments are conducted. The inset shows a horizontal phase-space diagram following the HCX electrostatic transport section where the beam filled 80% of the aperture (maximum excursion of the beam envelope). The coherent envelope expansion of the beam has been removed so that any phase-space distortions are clearly visible. The mismatch amplitude in the upstream transport channel was 1 $\pm$ 0.5 mm.

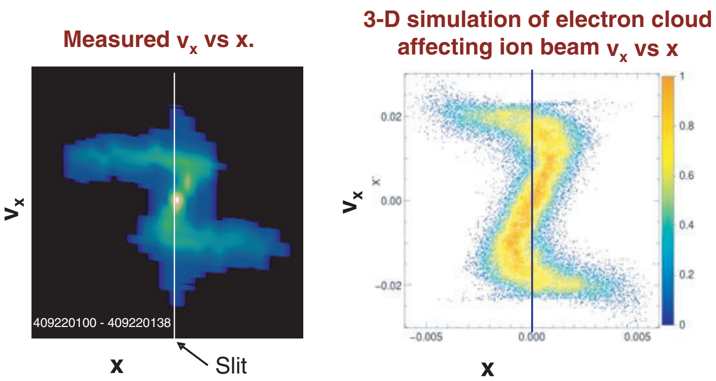

Figure 5. When secondary electrons are not suppressed electrostatically, electron clouds distort the phase-space of a 1 MeV, 0.18 A K^+ ion beam just after transport through four quadrupole magnets in HCX. V_x–x phase-space measured with a slit scanner just after the beam exits the last magnet (left panel), compared to three-dimensional self-consistent simulations of the experiment (right panel).

any preformed plasma (left panel), a spot size reduced by almost a factor of 10 with a localized ‘plug’ plasma just beyond the last focusing magnet (centre panel) and a further 25% reduction in FWHM of spot size is seen (right panel) when both ‘plug’ and ‘volume’ plasmas are used. The background plasma density is at least 10 times higher than the beam density everywhere downstream of the last focusing magnet. Particle-in-cell calculations using the hybrid LSP code [13] predict an rms spot radius of 1.4 mm for the case of a plug plasma (centre panel), in good agreement with the experiment. No evidence is seen for significant beam–plasma instabilities in these experiments, nor in the simulations.

2.4. *Scaled long-path experiments*

Long-path-transport physics experiments have begun with the University of Maryland Electron Ring [14] and with the Paul trap simulator experiment at PPPL [15]. These novel experiments allow the study of relevant driver beam dynamics over 100s to 1000s of lattice periods at modest cost.

2.5. *Theory and simulation*

The increased need to study gas and electron cloud effects, and to study beam–plasma interactions in the drift compression and final focus regions of neutralized beams has motivated much progress in advancing heavy ion fusion beam transport models and simulation codes to include multi-species effects and beam–plasma instabilities. Noteworthy are studies [16, 17] of two-stream instabilities caused by background electrons, of interest both to heavy ion fusion and intense proton storage rings. The effects of electron clouds on beam loss have been studied by including electron cloud models in WARP simulations [7]. New mesh refinement capabilities in WARP [18] and other improvements [2] have enabled very good agreement between injector simulations and measurements, including accurate time dependent rise of the current. Simulations of collective relaxation processes have shown the that surprising degrees of space-charge non-uniformity are tolerable. Integrated three-dimensional simulations of an integrated beam experiment have shown the development of a clean beam ‘tail’ and quiescent beam propagation. Simulations of temperature

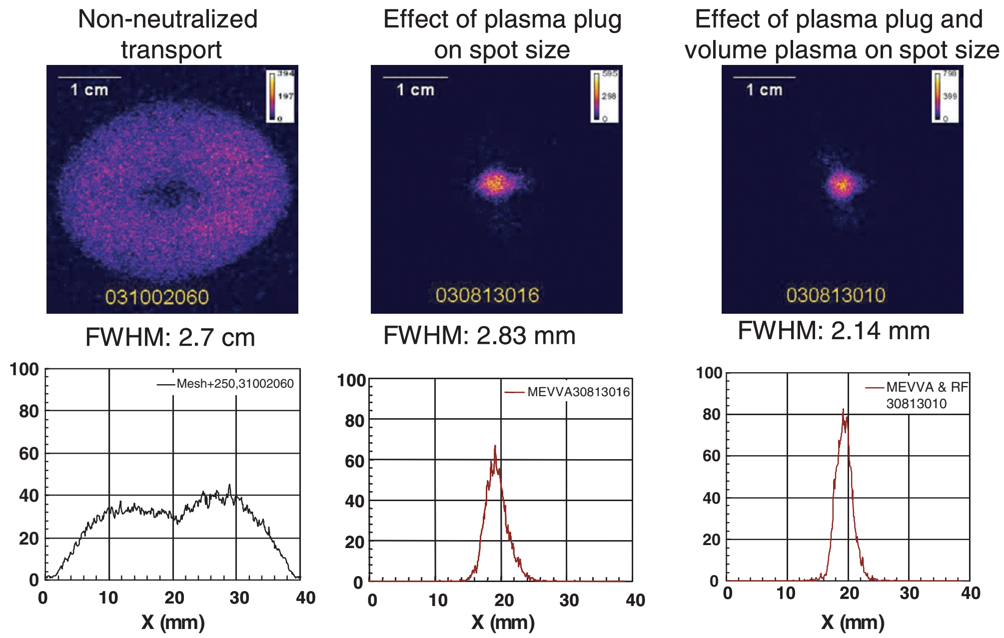

Figure 6. NTX showing beam images at the focal plane for three cases of space-charge neutralization for a high perveance (6×10^{-4}), 25 mA, 300 keV K^+ ion beam. Left: no preformed plasma; centre: localized 'plug' plasma just beyond the last focusing magnet; and right: with both 'plug' and 'volume' preformed plasma.

anisotropy modes [19] have recently been extended to three-dimension.

2.6. IFE chamber and target research

New heavy ion target designs ('hybrid-distributed radiator') have been developed that would allow much larger (5 mm radius) focal spots, and experiments to test symmetry features in such targets are underway in the Sandia National Laboratories Z-facility [20]. Processes have been identified to mass manufacture heavy ion hohlraum targets at low cost and to inject them at 5 Hz [21]. A new technique of periodic vorticity injection and ejection allows a new class of thick-liquid-protected large-vortex IFE chambers to be designed with flexible ranges of internal cavity shapes. A multiple-beam induction-linac-driven power plant study [22] shows that detailed requirements for distributed radiator targets (spot size, power, symmetry and pulse shape) can be met by neutralized ballistic focusing of 120 beam arrays (60 beam arrays from two sides) over 6-m focal lengths. A recent study shows that smaller focal spots may be obtained using negative ion beams. Provided neutralized drift compression and focusing and larger-spot hybrid targets can be experimentally validated, recent preliminary studies indicate that modular induction linac driver systems with about 20–40 linacs may be cost-competitive [23].

3. Research plans for neutralized drift compression and focusing

After acceleration, longitudinal drift compression by a factor of 10 or more, followed by focusing onto a target, has always been an essential step for any approach to heavy ion fusion. For less than a few hundred beams, longitudinal and radial confinement of ion beams undergoing either RF or induction acceleration are only manageable for pulse lengths long compared to the 10 ns requirement of the target. In the 1970s and 1980s, concerns about beam–plasma instabilities motivated the search for 'vacuum' solutions to heavy ion fusion that did not require plasma neutralization anywhere except in the target. However, vacuum solutions require high kinetic energies, of order 10 GeV, and many beams, likely 100 or more. Since 1995, the US programme has studied neutralization of converging beams with preformed plasmas after final focus to reduce projected driver voltage (2–4 GeV) to reduce cost. Both experiments and simulations have since shown that beam–plasma interactions after final focus can be beneficial overall, that is, starting with space-charge-dominated beams, plasma neutralization reduces the focal spot size significantly despite nonlinear residual electrostatic fields that can increase beam emittance during neutralization. Also, experiments and theory suggest beam–plasma instabilities can be suppressed if the background plasma density is sufficiently large compared to the beam density.

Several recent factors have motivated US research to consider neutralization of heavy ion beams with preformed plasma not only in the target chamber, but also in the drift compression region between the accelerator and the target chamber. First, recent theory and simulations suggest that there are several ways to focus the beams after longitudinal compression within background plasma, even with the coherent head-to-tail velocity tilt remaining from the drift compression in plasma. Beam–plasma instability studies for neutralized drift compression indicate instabilities in regimes with sufficient plasma $n_p \gg n_b$ and within embedded solenoid fields, may not strongly impair the final focus.

Figure 7 shows an illustrative simulation by D.R. Welch *et al* of the ATK Mission Research Corporation using the LSP code to assess a possible neutralized drift compression and focusing experiment using reconfigured NTX equipment.

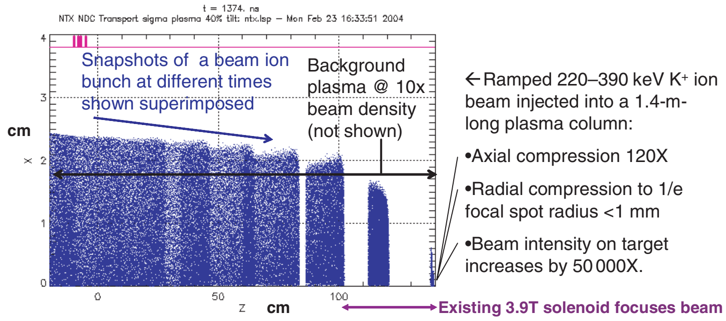

Figure 7. Particle-in-cell simulation of a possible experiment using NTX equipment to study longitudinal compression and radial focusing of an intense heavy ion beam within a neutralizing background plasma column. The peak beam current density exceeds 100 A cm^{-2} on axis. (Courtesy of D.R. Welch, ATK Mission Research, Albuquerque, N.M.)

The simulation in figure 7 shows >120× axial compression with >20× radial focusing, resulting in >50 000× increase in beam intensity at the focal plane. A series of three experiments with increasing beam compression and intensity on targets are envisioned.

Second, the US government has requested increased emphasis on near-term applications of heavy ion beams to HEDP studies, for which targets require very short pulses. For US heavy ion fusion experiments with heavy ion beam energies of a few mega electronvolt, the ion range is a few micrometres in solid targets, and so the ion heating pulse has to be or order or less than the hydrodynamic disassembly time, of order 1 ns at 1 eV. A planned goal is to show the feasibility of an approach to isochoric target heating to >1 eV with mega electronvolt-class heavy ion beams within 5 years. Recent work [24] has shown that isochoric ion heating of thin targets can be very uniform if modest energy ions enter the target with energies just above where $\mathrm{d}E/\mathrm{d}x$ peaks, and exit with energies just below the peak in $\mathrm{d}E/\mathrm{d}x$, such that the peak in $\mathrm{d}E/\mathrm{d}x$ occurs in the centre of the target layer. However, the high perveance of such beams for warm dense matter studies at 1–10 eV would require neutralized drift compression and focusing.

Finally, drift compression and focusing of neutralized beams may lead to the possibility of driving targets with linac voltages 10 or more times lower than required for ballistic focusing of un-neutralized beams [23]. For example, if neutralized neon beams of 200 MeV could be focused, a modular driver system of say, 20 short linacs in parallel, might have the same total combined linear length and voltage as the 4 GeV bismuth linac described in [18]. Such a modular driver would allow tests with one module for a driver, lowering the development cost for heavy ion fusion energy. In fact, neutralized drift compression and focusing may also reduce the linac voltage, length and cost for multiple-beam quadrupole linac drivers as well.

Scientific issues for neutralized drift compression and focusing (key areas for further research) include:

(a) Injection/acceleration/bunching to required high perveance ($>10^{-2}$) and with sufficiently low parallel and transverse emittances before plasma neutralization to allow the desired large beam compressions in plasma.
(b) Beam transitions at high line-charge densities from Brillouin flow into neutralizing plasma columns with tolerable emittance increases while preventing electron back-flow.
(c) Control of beam plasma instabilities over long regions of drift compression in background plasma, and controlled stripping, which do not interfere with final focusing to required target sizes.
(d) Extension of neutral final focus to longer standoff distances with uncompensated velocity tilts, sufficient to meet either neutralized ballistic focus or assisted-pinch transport radii.
(e) Validation of symmetry control in large-focal-spot hybrid targets for IFE.

4. Conclusions

Recent experiments and simulations have significantly advanced the physics knowledge base needed to optimize the design of future heavy ion accelerators designed to drive HEDP targets with ions just above the Bragg peak in $\mathrm{d}E/\mathrm{d}x$, and for heavy ion accelerator drivers for IFE. Two driver options are being explored: a multi-beam quadrupole-focused linac and modular, separate solenoid-focused linacs. Future experiments aim to develop a predictive capability for electron cloud effects, and for the limits of beam compression and focusing of neutralized beams with head-to-tail velocity ramps travelling within background plasmas. If successful, such experiments may enable near-term experiments for isochoric heating of targets to 1 eV, and further the possibility of modular linac approaches to heavy ion fusion.

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